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Teacher's Guide for NF-58 Comparing the Planets

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Introduction
Purpose of the Solar System Chart

This chart of the solar system has been designed as a teaching aid and a tool for self study for all grade levels. Material has been selected and arranged so that the more advanced student can extract additional information by comparing the various parts of the chart. Depending upon the amount of knowledge and intellectual development of the viewers, they can use the chart for discovery experiences, confirmation and reinforcement of knowledge which they already possess, and integration of diverse concepts.

The study of the solar system has matured within the past twenty years. The ability to study the planets at close range through the use of space probes has been a driving force in the development of the science of the solar system. Investigations using Earth-based telescopes continue to play an important role, as do theoretical studies making use of modern computers. Space probes have flown past or orbited Mercury, Venus, the Moon, Mars, Jupiter, and Saturn. In addition, spacecraft have landed on Venus, the Moon, and Mars. Each step of exploration has brought great new levels of understanding. It is now possible to understand some of the reasons why the planets have the characteristics that they have, and why there are similarities and differences among them. As the decade of the seventies draws to a close, the science of *Comparative Planetology* is beginning. Questions about the origin of the solar system, and of life itself, are now being posed and partial answers have been found.

Scientists who are studying the Earth are able to draw upon knowledge of the other planets to further their investigations. We can learn about the Earth's climate from the study of our neighbors, Venus and Mars. Venus, which was once expected to be about 50°C (Celsius) hotter than Earth, is instead more than 400°C hotter because of its dense atmosphere of CO_2. This is the same gas which is even now contributing to the increase in Earth's temperature, though at the much smaller level of less than one degree. Studies of Mars reveal that it once had streams of liquid water and maybe even rain. Its climate has changed now and the planet is a cold, dry desert. The reasons for this climate change may be related to slow changes in Mars' orbit around the Sun. Similar changes have been suggested to account for the ice ages on Earth.

In addition to those things which we can learn about Earth from comparing the planets, we can now understand the solar system as a self-contained entity. For example, it has long been known that the outer planets (Jupiter, Saturn, Uranus, and Neptune) are much larger and more gaseous than the inner planets (Mercury, Venus, Earth, and Mars). This can now be understood as resulting from the differences in their compositions due to the conditions in the solar system when they were formed. Each object in the solar system, the nine planets, 34 known satellites, tens of thousands of asteroids, and countless meteoroids and comets, is a space probe. Each carries with it the encoded history of some part of the solar system. Modern space science is unraveling those codes to learn the history and the basic nature of the solar system.

The chart is up to date as of mid-1979, including the discoveries of the most recent investigations, and has been designed to provide the student with a framework for understanding and integrating the results of future studies.

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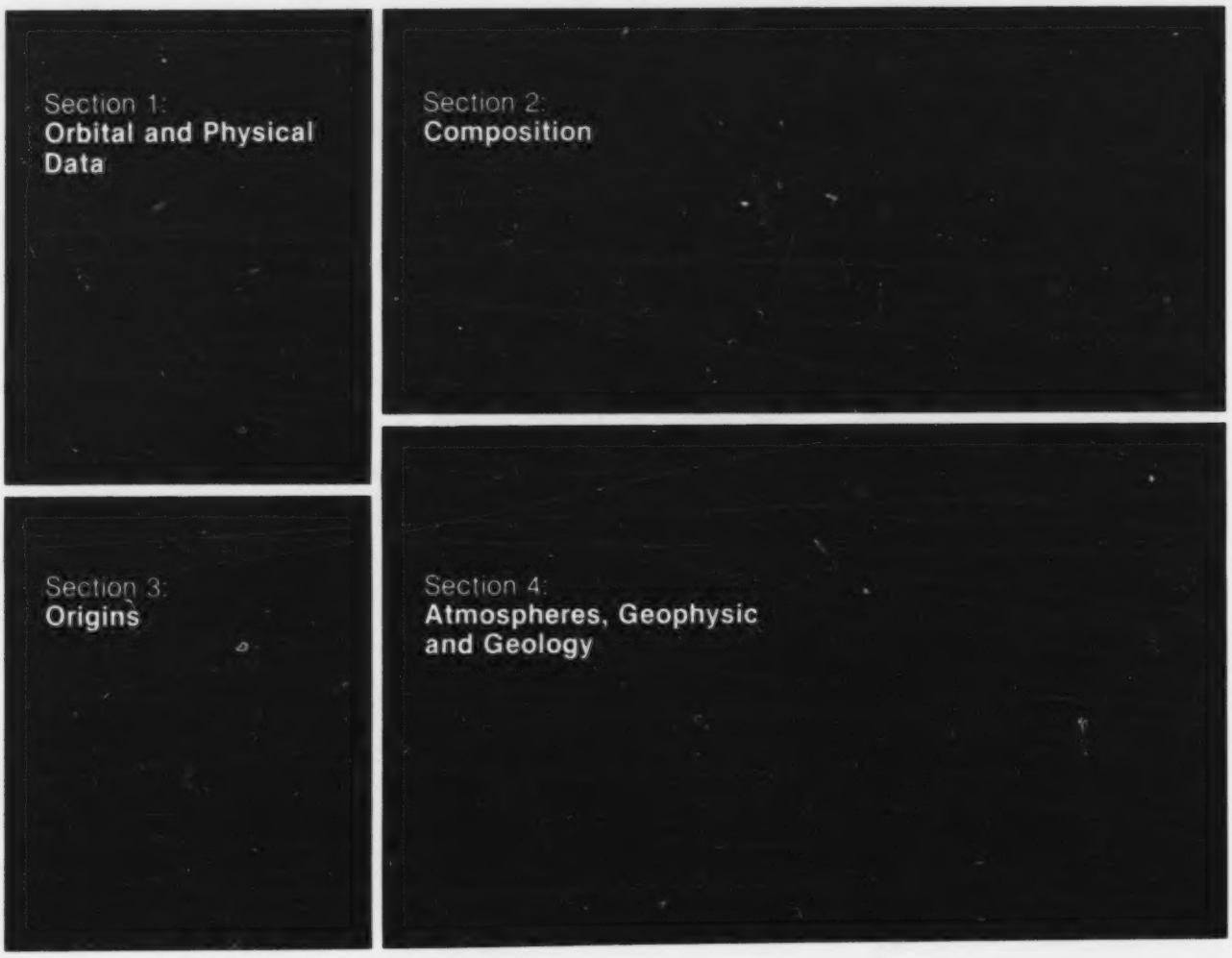
Section 1:
Orbital and Physical Data
Section 2:
Composition
Section 3:
Origins
Section 4:
Atmospheres, Geophysic and Geology

How to use the Chart

The chart is divided into four major sections. The upper left portion presents the planets and their orbits about the Sun and tabulates the current data on their orbital and physical characteristics. The remainder of the upper portion of the chart is used to display the best available images of the planets, set into a graphical framework which shows how the composition of the planets, as measured by their densities, changes throughout the solar system. The lower left section explains current theories of the origin of the solar system. The remainder of the lower part of the chart is used to introduce the science of *comparative planetology* through a series of mostly visual comparisons made possible through twenty years of space exploration. Each of these sections will be discussed in some detail below.

An important first step toward the teaching of *comparative planetology* is to draw attention to the dichotomy between the inner and outer planets. This point is emphasized in the first section of the chart, with the demonstration of the much greater distances of the outer planets and their larger sizes. The two phenomena are related through processes which are only partially understood. In the composition section of the chart, the outer planets are seen to lie systematically to the left side of the "graph" because of their lower density. The inner planets lie to the right, and the Moon near the center. If other satellites were shown, they too would lie in this middle region. The differences in their densities are clues to their origins.

The second step in *comparative planetology* is the detailed comparison of features and physical phenomena on the planets. The lower portion of the chart provides this opportunity.

Section 1:
Orbital and Physical Data

The planets move around the Sun in nearly perfect circles, and all but Mercury and Pluto lie very nearly in the same plane. The chart presents a perspective drawing of the orbits, causing each orbit to appear as a highly flattened ellipse*. Because of the tremendous differences in the distances from the Sun, a single drawing cannot adequately represent the true spacing, so the orbits of the inner planets are displayed at a ten-fold enlargement above the drawing of the entire system.

The relative sizes of the planets are also shown in this section and their relative volumes indicated below. The oft-quoted relative diameters of the planets do not adequately portray the true differences; Jupiter is about 11 times the Earth's diameter, but more than 1300 times its volume! In the second part of the chart (Composition) the inner planets are shown to one common scale, and the outer planets to a different common scale.

The tabular data need little elaboration. Most of the numerical data are well established except for the rotation periods of Uranus and Neptune and the size and mass of Pluto. Students may be interested to notice that the rotation period of Mercury is exactly ⅔ of its period of revolution around the Sun due to tidal distortion of Mercury's shape. Venus' rotation is slower than that of any other planet and in the opposite direction from all others except Uranus. The center of mass of the planet is about 1.5 km away from its geometrical center. Further, the same side of Venus always faces Earth at closest approach. Interested students may wish to compare data for the various planets and pose hypotheses as to why the numbers are what they are. Why, for example, are the poles of five planets tilted between 25° and 30° from their orbit planes, and why is Uranus tilted so far that its pole almost lies in its orbit plane? These questions are unanswered. Today's students will no doubt provide the answers tomorrow.

* The actual orbits are also ellipses, but if viewed from above they would be all but indistinguishable from perfect circles. Mercury, Mars, and Pluto are the exceptions. Careful examinations of the drawing will reveal that, for them, the Sun does not lie at the center of the ellipse but at its focus.

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Section 2:
Composition

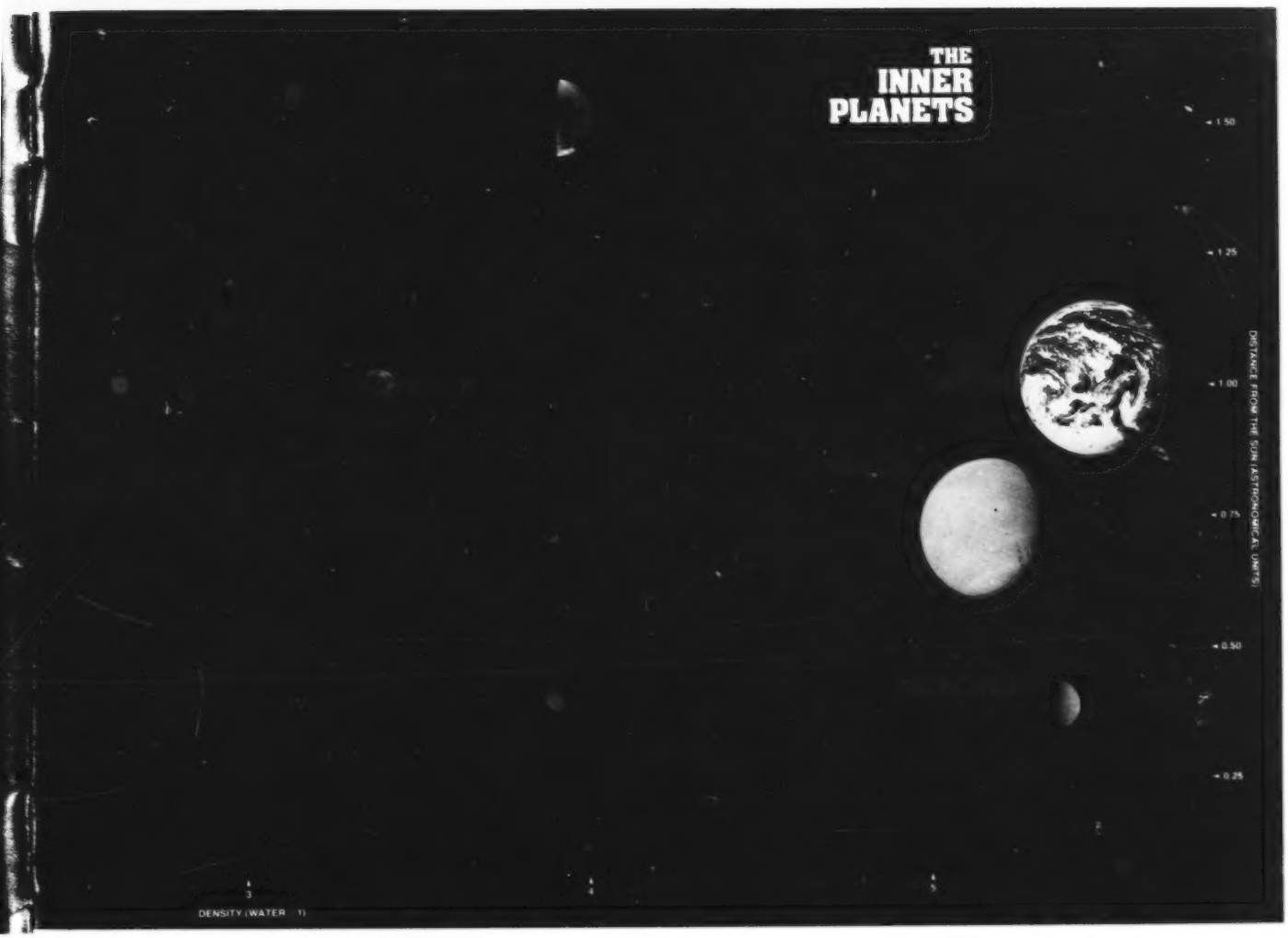
The planets are displayed in an array which is actually a type of graph. The X axis is the density of the planet. The Y axis is the distance from the Sun. An expanded Y axis scale is plotted on the right hand side. The left hand scale is used for the outer planets (40 A.U. to 2 A.U.) and the right hand scale for the inner planets (less than 2 A.U.). The relative sizes of the outer planets are shown to a common scale while the relative sizes of the inner planets are shown larger by a factor of 10.

Depending on the level of the class, the concepts outlined below can be explained in detail, or the graph can be used as a visual display simply showing that the planets are clearly separated into two classes. The outer planets, lie to the left of the array, indicating their low densities. They are composed almost entirely of the light elements hydrogen and helium, which are the major components of the universe. The inner planets lie to the right of the array because of the concentrating of heavy elements such as iron and silicon. Since these heavy elements are relatively rare in the universe, some mechanism for concentrating them into the inner planets is needed. The series of displays in the lower left of the chart (Section 3) explain our current thinking about the origin of the solar system which resulted in this concentration.

A closer look at the inner planets shows a trend toward lower density as one examines planets farther from the Sun. The trend is even more striking when you consider that a planet made of the same material as Mercury, but as large as Earth, would be at least 20% more dense than Mercury because it would be compressed by its own gravity. Venus stands against the trend in density, possibly due to the absence of sulfur from its interior. Curiously, there is an abundance of sulfur in the Venus atmosphere. Composition of planetary atmospheres is discussed in the next section.

The details of the outer planet densities are less clear-cut. The trend from the inner solar system continues through Jupiter and Saturn, with Saturn being lower in average density than water. In other words, given a large enough ocean, Saturn would float! But the trend reverses, with Uranus almost equalling Jupiter in density and Neptune exceeding it. Recalling that the self-compression due to the planet's gravitation will cause a large planet to be relatively more dense than a small one of the same composition, we see that Uranus and Neptune are apparently quite different in composition from Jupiter and Saturn.

Pluto remains an enigma. Because of its remoteness, very little is known about its nature. It is certain, however, that it is not a gaseous planet like the other outer planets. It is far smaller



and probably much denser. Some have speculated that it may be an escaped satellite of Neptune. Referring back to section 1, notice that the orbit of Pluto actually crosses inside that of Neptune. Recent investigations indicate that Pluto has a satellite.

Other objects, such as natural satellites and asteroids, could be placed in the diagram as well. If they were, they would lie in the range between 1 g/cc and 3.5 g/cc. Very low densities, much less than 2 g/cc, are possible only if the object is composed largely of ices. This may be the case for some of Jupiter's and Saturn's satellites. The techniques for measuring their sizes and masses are difficult and the uncertainties in the results are large, especially for Saturn's satellites. Other satellites such as those of Mars, and a number of asteroids range between 1.5 and 3.5, indicating either that they are similar to a type of meteorite called a carbonaceous chondrite (density 2) or stony meteorites (density 3-3.5). Iron meteorites, with densities near 9 g/cc, have been found, which suggests that asteroids of similar density may well exist.

In summary, the density of an object may be used to characterize its bulk composition if allowance is made for the self-compression by gravity of larger objects. There are other techniques for studying composition, such as spectrographic and photometric investigations of the atmospheres and surfaces of planets, or even the direct laboratory study of samples. Some of the ways in which these methods have been used are discussed along with imaging systems in the third section of the chart.

Section 3:
Origins

The variations in composition discussed above are best explained by a theory of origin of the solar system in which the Sun and all other solar system objects condensed out of a huge mass of gas and dust called the proto-solar nebula. (Nebula is the Latin word for cloud.) This section shows an artist's conception of this giant cloud as it may have looked some 4.6 billion years ago and a graph of the temperatures which may have prevailed at different distances from the proto-Sun. At the higher temperatures close to the proto-sun only the comparatively heavy elements with high melting points were able to condense into the liquid state or freeze into the solid state. These elements, while extremely rare compared to the more abundant hydrogen and helium, were thus enriched as the inner planets formed. Planets forming further from the proto-Sun at lower temperatures were composed of the more abundant light elements which were able to condense at those temperatures. This concept explains the density variations shown in the chart which were discussed in Section 2.

The variation in composition for the inner and outer planets is graphically displayed with two representations of a periodic table. The heights of the columns over each element represent the relative abundance compared to oxygen. If the amounts of hydrogen and helium in the outer planets were shown to scale, they would extend past the top of the chart.

The Sun contains more than 99% of the mass of the solar system and the planets more than 99% of the remainder, but the countless smaller bodies of the solar system provide some of the best clues as to the forces which caused the solar system to form. Jupiter, for example, shows us one way in which an object at a particular portion of the solar nebula might evolve. Jupiter's 13 satellites provide 13 additional probes of space and time to show some of the subtle varieties which can and did occur. In fact the densities of the four largest satellites show a trend toward lower densities as one examines those further from Jupiter. This suggests that Jupiter may have been a local hot spot in the solar nebula and thereby affected which elements were able to condense into satellites in Jupiter's vicinity.

Section 4:
Atmospheres, Geophysics, and Geology

This section consists of a number of comparisons between the planets. It shows that there are some striking similarities between phenomena observed on the various planets. The comparisons are loosely grouped into three categories: Atmospheres, Geophysics, and Geology. Students at the lower levels will find it interesting to see pictures of similar features on Earth and Mars while more advanced students may wish to examine the factors which distinguish one planet from another.

As an example of how these additional comparisons can be made, consider the volcanoes on Earth and Mars, which are qualitatively similar. The tallest Martian volcano, however, is nearly 26 km high where the tallest mountains on Earth rise only 8 km from their base. The reason for this difference, as indicated in the expanded picture captions which follow, is that Martian gravity is less than Earth's and therefore gravitational slumping (properly called isostatic adjustment) is less pronounced. Another factor, perhaps of equal importance, is that Mars does not have active continental drift occurring as does Earth, and the energizing source of hot magma in the mantle has been under the same part of the crust for most of the 4.6 billion year history of the planet. Volcanoes on Earth are thought to derive their energy from plumes rising from the mantle to the crust. But Earth's crust is moving due to the forces of continental drift and the volcano literally moves away from its magma source in a few tens of millions of years.

Extended Remarks on Comparisons

Atmospheres

Atmospheres are found on seven of the planets and one satellite (Titan). Only the smallest planets, Mercury and Pluto, have been unable to retain an atmosphere over the 4.6 billion year history of the solar system. It is thought that the atmospheres of the terrestrial planets were outgassed from the interiors of the planets as they cooled. Earlier in their history, they may have had atmospheres rich in hydrogen and helium, the most abundant elements in the universe. These light gases were lost to space because, at the temperatures encountered in the inner solar system, the molecules moved rapidly enough to escape the planets' gravitational pull. Mercury is so close to the Sun, and of sufficiently small mass, that it could not even retain its secondary atmosphere of heavier gases such as those found on the other terrestrial planets. Whatever atmosphere Pluto might have retained has been frozen to its surface in the deep cold of its far orbit. Indeed, a reflective coating of frozen methane has been found on Pluto.

The outer planets — Jupiter, Saturn, Uranus, and Neptune — have retained their primordial atmospheres of hydrogen and helium. The gases methane (CH_4) and ammonia (NH_3) are seen in the spectra of Jupiter and Saturn, and NH_3 is important in the formation of Jupiter's colorful cloud belts. The amount of other gases are quite small compared to hydrogen.

Saturn's satellite, Titan, has an atmosphere of CH_4 and possibly nitrogen and hydrogen. Titan is comparable to the Moon in size, but the lower temperature (at nine times the Moon's distance from the Sun) allows it to retain its atmosphere.

Atmospheres may be studied by a variety of techniques. In this chart we have concentrated on visual comparisons which tend to emphasize the effects of clouds. Our understanding of the composition of the atmospheres comes not so much from examination of photographs as from the study of the spectra of the planets to identify the atomic and molecular constituents. For two of the planets, Mars and Venus, samples have been analyzed by laboratories carried to the planets' surfaces by space probes.

Clouds are formed when a gaseous component of the atmospheres becomes liquified or solidified as temperatures or pressures drop. On Earth, clouds are formed when water vapor (a gas) condenses into tiny droplets. Sometimes at higher altitudes the water freezes into small ice crystals to make the thin wispy clouds known as cirrus clouds. Windblown dust can also form into clouds. Space photographs have revealed huge dust clouds from the Sahara desert stretching across the Atlantic Ocean.

The clouds of Mars are similar to the terrestrial cirrus clouds, in that they are ice crystals. Unlike those of Earth, they are usually formed from CO_2, the dominant component of the atmosphere. There is a trace amount of water in the atmosphere of Mars, and clouds of water ice have been seen from time to time. Clouds of water droplets such as are common on Earth could not exist at the low temperatures and pressures of Mars' atmosphere. Mars also has extensive dust clouds, sometimes covering the entire planet.

On Venus, where the temperatures and pressures are much greater than on Earth, clouds of water ice or water droplets are not possible, yet the planet's surface is perpetually obscured by the clouds. The clouds are composed of droplets of concentrated sulfuric acid and perhaps elemental sulfur. Like the terrestrial clouds, they are made from a minor component of the atmosphere.

Perhaps the most beautiful clouds are found on Jupiter. The temperatures and pressures in the visible regions are compatible with clouds of water ice, but spectrographic evidence for the proper amount of water vapor is not found. Theoretical calculations suggest that the uppermost layer of clouds is a layer of ammonia (NH_3) cirrus, and deeper layers are ammonium hydrosulfide. The source of the colors has been the subject of much investigation, but no convincing answers have been forthcoming.

Clouds are good indicators of the motions of the atmospheres of the planets. If either the temperature or the pressure of the atmosphere increases sufficiently, the cloud material can be vaporized and the cloud will disappear. A parcel of moist atmosphere which is rising will tend to be cloudy, since both the temperature and pressure decrease as the air rises. Eventually, the rising air will become drier as it loses its moisture to the clouds and the air will become cloud-free at high altitude. On the Earth there is a band of clouds near the equator caused by just such a phenomenon. The high altitude dry air is then driven

towards the middle latitudes. The high altitude air descends to lower altitudes, further inhibiting the formation of clouds as it is heated by compression. As a result, the region between 10° and 30° latitude is relatively cloud free. A second region of rising air, lower average temperatures and latitudinal air flows cause much of the region poleward of these zones to remain cloudy much of the time. These features are indicated on the picture of Earth in Section 4 and are less clearly seen on the Earth picture in Section 2.

The light colored zones and dark belts on Jupiter are probably caused by the same types of phenomena. On Jupiter, however, the rapid rotation (less than 10 hours) gives rise to a series of zones of clouds and belts of cloud-free regions which are clearly delineated.

The cloud patterns on Venus are less well understood. It is known from infrared investigations which measure the planet's temperature that there is very little difference in temperature from day to night or from equator to pole. The upper atmosphere rotates at high speed forming Y-shaped markings of clouds. A rising column of hot air at the subsolar point* apparently disrupts the flow of the atmosphere causing ripples in the flow. Just as a boat churning through the water creates a "bow wave" so too does this rising mass of Venusian air. The same phenomenon, on a much smaller scale, is seen when moist air passes an isolated island on Earth, such as the Antipodes Islands, or a prominent peak such as a mountain or high-walled crater on Earth or Mars.

*The subsolar point is the place on a planet where the sun is directly overhead.

Geophysics

The term geophysics originally meant the physics of the Earth, but it has been broadened to include all of the planets. It concerns such topics as the physical processes which affect the interiors and surfaces of the planets. The study of the atmospheres could be included as well; the dividing lines between fields are not clearcut. Planetary geology is concerned with the appearance of the surfaces and the description of the processes which affect it.

A major revolution has occurred over the past decade in our understanding of the physical processes which affect the surface and near surface of Earth. The phenomenon of plate tectonics (more loosely called continental drift) is now understood rather well, and can explain most of the major geological features of Earth: continents and oceans, the locations of earthquakes and volcanoes, origins of mountains, etc. Space age capabilities allow similar studies to be carried out for some of the other planets as well.

It is now apparent that Earth is a more active planet than the other terrestrial planets. This activity is evidenced by the ocean basins and continents, and by volcanoes and folded mountains, by earthquakes, and perhaps by the very nature of its atmosphere. No other planet is divided into two such distinct types of surfaces as continent and ocean basin, but other planets do tend to have hemispheres of different types. The far side of the Moon, for example, has almost no dark areas such as are prominent on the near side.

Mars has been the next most active planet over geologic time. It too has huge volcanoes, but it has no folded mountains like our Appalachian Mountains which were formed when two continents (Africa and North America) collided. The fact that its volcanoes are taller than our tallest mountains also attests to its lower activity. The driving heat for volcanoes comes from the deep mantle or from one continental plate being forced under another. On Earth, the part of the crust which is over a mantel "hot spot" is constantly changing, so that there is not time enough to build such huge volcanoes as those found on Mars. Similarly, without drifting continents to push one continental plate under another, there is no source for that type of volcano on Mars. Mars has relatively few, but very well defined, large volcanoes. They probably have been inactive for over one billion years.

The Moon is even less active than Mars. It does have some inactive volcanoes, but as seen on the chart, they are small structures compared to those on Earth or Mars. The Moon's Marius Hills are only a few hundred meters high. No volcanoes have been identified on Mercury, but a number of long *scarps* (cliffs) have been seen. Analogous scarps on Earth are caused by compressional forces, and it is thought that those on Mercury were formed in a similar manner. Early in its history radioactive heating caused the interior of the planet to remelt, allowing the iron and other heavy metals to settle to the center to form its core. Once that had happened and the crust reformed, the planet shrank as the core cooled down. The shrinking of the planet caused the compressional forces which created the scarps.

The surface of Venus remains largely a mystery because of its thick cloud layers. Radar studies of the surface have revealed some long linear features which may be ridges caused by tectonic forces. Since we anticipate that tectonic activity will be correlated with planet size and density, some form of tectonics on Venus which exceeds that of Mars would not be surprising. A radar mapping experiment from the Pioneer Venus orbiter has revealed large plateaus several kilometers above the surrounding terrain, mountain peaks comparable to Earth's largest, and long, deep troughs.

Earthquakes are excellent indicators of tectonic activity and internal structure. A plot of the locations of earthquakes on Earth outlines the individual continental plates. Limited seismic studies have been made on the Moon and Mars. Moonquakes are caused either by impacting meteors or internal motions. There are at least a hundred times fewer moonquakes than there are earthquakes, confirming the lower level of tectonic activity on the Moon. One interesting aspect of the moonquakes is their long duration, as explained on the chart.

Only one of the two seismometers placed on Mars by NASA's Viking spacecraft worked properly, but there have been no confirmed Marsquakes to date, also indicating its lower level of activity.

Magnetic fields are generated deep in planetary interiors as a result of the planets' rotation and an electrically conducting fluid in its core. Earth and Mercury have magnetic fields, while Venus does not. Apparently the rotation period of Venus (243 days) is too slow to generate a magnetic field, while the Mercurian rotation period of 59.6 days is sufficient. The Moon has only a weak remanent magnetic field which is left over from the past. It is not clear whether or not the Moon has a core. Rapidly rotating Jupiter most certainly possesses a magnetic field, one which is at least twenty times stronger than Earth's. Rather than originating in an iron core, Jupiter's magnetic field comes from its metallic hydrogen core. Both Jupiter and Saturn are the source of bursts of radio energy. In the case of Jupiter they are associated with the magnetic field so it seems reasonable to assume that Saturn also possesses a magnetic field.

The Earth's magnetic field protects it from the onslaught of energetic particles in the solar wind. If these charged particles which are deflected by the magnetic field were to reach Earth continously, the composition of the atmosphere and perhaps even the nature of life itself would have been vastly different. A planet like Venus lacks this protection.

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Geology

One of the more interesting but rare geologic features found on Earth is the impact crater. Because of the detailed exploration of the Moon and the reconnaissance of the other terrestrial planets we now know that such craters are common elsewhere in the inner solar system. This puts scientists in the unique position of knowing that something which is not now present in abundance must once have been common. Laboratory investigations of the returned lunar rocks have revealed their ages and the times which they underwent major changes such as partial remelting.

It is clear that all of the inner planets were heavily bombarded by meteors from their formation 4.6 billion years ago down to 3.9 billion years ago. On Earth the evidence of that early bombardment has been erased by the combined forces of erosion, sedimentation, and tectonics. The oldest rocks on Earth are but 3.7 billion years old, and the vast majority are far younger still. The chart shows pictures of craters on Earth, Moon, and Mars. No attempt has been made to show craters of comparable size. The meteor crater on Earth has been shown as a small spot against a craterless terrain to emphasize rarity of these features on Earth. Both the Moon and Mars contain a wide variety of crater types which show considerable variation in appearance; the Martian crater with lobate flows is one of the more common types and has an interesting interpretation. The lunar crater featured is a young one with older craters included in the field. Mercury and the satellites of Mars are also heavily cratered, each with distinctive characteristics. Venus also seems to be crater-marked, although intepretation of radar images is not as straightforward as that of photgraphs. If the features detected on Venus are meteor craters, it is an indication that Venus is not as active as Earth where most of the meteor craters have been destroyed by erosion and continental drift.

Just as the Earth-based geologist is able to use physical and chemical tests to study the material at or near the Earth's surface, the planetary geologist can place instruments into orbit around a planet to remotely sense its nature. One such example is the gamma rays made by Apollo astronauts as they orbited the Moon. Diffferent elements emit gamma rays of characteristic energies. By measuring the amount of gamma ray energy over a particular spot they can estimate that amount of that element in the near surface of the planet. This technique was used by the Russian spacecraft Venera 9 and 10 to characterize the material at the sites on Venus at which they landed. Both were found to be similar to terrestrial plutonic rocks, one a basalt and the other a granite.

A picture of one of the Venus sites is shown on the chart together with a scene from one of the NASA Viking spacecraft on Mars and a picture in the dry valleys of the Antarctic. One is immediately struck by the similarity between the Antarctic scene and Mars. Because the geologic processes in the dry valleys are thought to be similar to those on Mars, NASA conducted a number of investigations there prior to the lauch of Viking. Extreme cold (-70°C) and dryness (it never snows) and high wind velocities simulate the Martian conditions.

Life

No discussion of comparative planetology would be complete without a discussion of life. To date, the only planet known to contain life is Earth. The lack of positive findings on Mars is of considerable interest because it shows that, at least in this one case, life apparently could not evolve in the hostile environment where the Viking landed. Questions remain as to whether life once existed in an earlier, milder climatic period. It is known that the climatic conditions on Mars do vary as the tilt of its polar axis changes over 40,000-year periods.

Unknown factors seem to have worked together so that at least once in its history Mars had running water at its surface. Dendritic (branching) stream channels are found in abundance on Mars as they are on Earth. Water is essential for life as we know it, so the past abundance of water on Mars gives us optimism that the phenomenon of life was once present.

Jupiter and the outer planets may hold some of the keys to the origin of life. Their atmospheres, rich in hydrogen, are similar to Earth's primitive atmosphere before the fast-moving light molecules of hydrogen and helium escaped Earth's gravity. Laboratory studies indicate that a Jupiter-like atmosphere is needed to create the first and simplest life forms at the molecular level. In this respect, the outer planets and Titan may act as time machines, enabling scientists to study the conditions of primitive Earth and to understand better the origins of life and the human population.

Glossary

Asteroid — A solid body (minor planet) smaller than a planet which orbits the Sun independently of a planet. Although the largest ones are similar in size to the larger satellites, they are of a different origin.

Astronomical Unit (A.U.) — The average distance between Earth and Sun, approximately 155 million km (93 million miles).

Atmosphere — Gases and suspended solid and liquid material which are gravitationally bound to the region around a planet or satellite.

Comparative Planetology — The technique of studying the nature of planets and other solar system objects by comparative studies of related objects.

Composition — The chemical makeup of an object. Composition can be specified by bulk density, fractions of the various chemical elements, or detailed specification of molecular and/or mineralogical abundances.

Continental Drift — The theory, now widely accepted, that the continents and ocean floors are made of a number of "plates" which move about over the hotter mantle. Typical motions are about 1-2 cm per year. Earthquakes and volcanoes are found primarily at the junctions of such plates.

Density — The amount of mass of material in a specified volume. The density is a measure of composition and the physical environment. A substance, when compressed by overlying material, will have a greater density than it would if it were formed at the surface of a planet.

Element — The basic building blocks of all substances: hydrogen, helium, etc.

Isostatic — Equal pressures. The outer layers of a planet tend to flow (over suitably long times) so that the pressure from overlying material is equal. Thus, when a mountain is formed the region beneath it will be of lower average density so that the total pressure at some depth is equal to that found where there are no mountains.

Lobate — Curved, rounded.

Mass The amount of material. Similar to weight except that the weight of an object depends upon the strength of the gravitational field. Even in zero gravity an object has the same mass, and requires the same amount of force to move it, as it does at our Earth gravity.

Meteorite A small piece of interplanetary material which has struck Earth. Before it falls on Earth it is known as a meteor. Meteors may be fragments of asteroids and comets.

Nebula A cloud of material. The solar nebula was a huge diffuse cloud, perhaps three times as massive as the Sun, out of which the solar system bodies condensed.

Orbit The path which one object describes around another due to their mutual gravitational attraction.

Outgassing The process by which gaseous material escapes from the liquid or solid regions of an object through volcanic action or other means.

Photometric Properties of an object relating to its brightness, color, and nature of reflection (ranging from diffuse, such as paper, to specular, like a mirror).

Planet One of the nine large nonluminous bodies in the solar system. The distinction between a planet and a satellite may not be clearcut except in that a satellite orbits around a planet. Our Moon is nearly the size of Mercury, and is closer to the size of its parent planet than any other satellite-planet combination. Similarly, Titan has many characteristics normally attributed only to a planet.

Satellite A smaller object in orbit about a larger one. See planet.

Scarp A sheer cliff.

Spectograph A device for analyzing light by separating it into its various colors. Substances can be indentified by the colors in which they emit or absorb light.

Tectonic The constructional process which creates features on a planetary body. Features may also be created by erosional or impact processes.